detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CISA

A COMPOSITE INDEX FOR PREDICTING PERFORMANCE OF MUNICIPAL SOLID WASTE INCINERATION SYSTEMS

Disha Joshi [1,*], Roshni Mary Sebastian [2] and Babu J. Alappat [1]

[1] *Department of Civil Engineering, Indian Institute of Technology, Delhi, India*
[2] *Department of Environment and Climate Change, Government of Northwest Territories, Canada*

Article Info:
Received:
30 November 2025
Revised:
12 February 2026
Accepted:
31 March 2026
Available online:
3 May 2026

Keywords:
Waste to energy
MSW incineration
Multi-criteria decision making
Environmental index

ABSTRACT

Municipal solid waste incineration is pivotal in contemporary waste management strategies, offering waste mass and volume reduction, energy recovery, and pathogen destruction.However, it depends on various operational, environmental and economic parameters that affect the performance of an MSW incineration system, and their optimization is essential for maximizing efficiency, minimizing environmental impact, and ensuring sustainable incineration operation. This creates a need for developing a simple yet robust tool to evaluate and benchmark the incineration performance. This study develops a composite index to predict the performance of an MSW incineration plant based on the key parameters known to influence its performance or performance prediction. The index assesses 12 parameters over three categories to rank various MSW incineration facilities based on their performance. It does this by expressing the performance in the form of a numerical value ranging from 0 to 100, where a higher index value implies better performance of the incineration plant. It is developed using a multi-criteria decision-making (MCDM) approach by incorporating the expertise of more than 150 experts from the field of solid waste management. The literature review helped identify 21 parameters that were known to affect MSW incineration performance. Then, expert opinions were utilized to cut down and prioritize these 21 parameters to the 12 most crucial ones using the Fuzzy Delphi-Fuzzy Analytic Hierarchy Process. The index is then finally constructed by aggregating the weighted scores of these identified parameters. The proposed index is then demonstrated using hypothetical plant data from three MSW incineration plants. It reflects the effectiveness of this tool in predicting and comparing the performance of MSW incineration plants. This tool will be valuable in assessing overall incineration plant performance. It can also be utilized by policymakers, plant operators, and academicians to improve and optimize the performance of the MSW incineration system.

1. INTRODUCTION

Rapid urbanization, industrialization, and increased population have led to increased waste generation, posing a challenge regarding its management and disposal. Globally, waste generation is projected to rise by 70% by 2050 (Planning Commission Submission Certificate of the Report of the Task Force, 2014). Therefore, it is imperative to identify strategies for sustainable waste management that reduce environmental impact and help with resource recovery (Wang et al., 2024). Among the available waste management strategies, MSW incineration is one of the promising ones and has become an essential part of the waste management sector. It simultaneously addresses multiple objectives of an efficient waste management strategy as it allows waste mass and volume reduction by 85% and 90% respectively, destroys pathogens, and recovers usable energy and material (heavy metals, for example) in this process (Ouda et al., 2013). The performance of an MSW incinerator is multifaceted; that is, it depends on various parameters broadly classified as operational, environmental, and economic. These wide range of parameters and their interdependence make assessing the overall plant performance challenging. Traditionally, researchers have conducted studies focusing on individual parameters to determine their impact on the MSW incineration plant performance. These evaluations typically were based on single metrics for example combustion efficiency, loss on ignition, toxicity characteristic leaching procedures, pollutant emission standards or techno-economic studies. However, there remains a lack of a holistic framework incorporating all the affecting parameters to assess the overall plant performance that can handle trade-offs between indi-

* Corresponding author:
Disha Joshi
email: disha.joshi@civil.iitd.ac.in

https://doi.org/10.31025/2611-4135/2026.19589

vidual parameters(Wehbe & Baroud, 2024). This creates a need for a comprehensive yet simple tool for evaluating the overall performance of an MSW incineration system. This tool will integrate indicators for process optimization, environmental compliance, and economic viability. It will help in straightforward cross-plant comparisons, tracking the plant performances on a routine basis, and communicating with stakeholders. This integration will be done by applying multi-criteria decision-making (MCDM) methods, which have found a wide range of usability in the waste management sector. The choice of methods for constructing this composite tool will determine its reliability, robustness, and practical applicability (Güdemann & Münnich, 2023).

Despite much research on the effect of individual parameters on the performance of MSW incineration, there is a lack of significant studies on an integrated performance evaluation framework that could act as a standardized comparison tool across different MSW incineration plants globally. This study is a demonstration of the steps involved in the construction of the Incineration Performance Index that addresses these gaps and quantifies incineration performance in the form of a numerical score ranging from 0 to 100, with higher values implying better performance in the form of high efficiency, better economics, and lower emissions. The index integrates all the operational, environmental, and economic factors into a single index and is used as a plant-level indicator. It measures the overall performance of an MSW incineration plant and is constructed in such a way that the parameters chosen for its construction also incorporate the impact of feedstock quality and intrinsic design parameters of the plant.

2. METHODOLOGY

2.1 Parameter Identification

A literature survey was conducted to help identify the parameters that affect the performance prediction of an MSW incineration system. This review helped us develop a list of 21 parameters, which were later narrowed down to the 12 most important ones using the Fuzzy Delphi method (Ishikawa et al., 1993), which incorporates the fuzzy theory (Zadeh, 1965) into the traditional Delphi method, which was incompetent in handling uncertainty, subjectivity, and ambiguity associated with expert judgements. This was done using the expertise of 120 experts worldwide, working in the field of solid waste management. These experts were provided with a questionnaire with the list of 21 parameters and were required to linguistically rate the importance of each parameter on a 9-point scale. Their responses were then converted to triangular fuzzy numbers. After iterative rounds of expert opinion, only the parameters with expert consensus and agreement > 75% and a threshold value of more than 7 were accepted for the next stage of parameter weighting; the rest were rejected. As a result, nine out of the initially chosen 21 parameters were dropped because they did not meet the selection criteria. Figure 1 shows the structural hierarchy for parameters affecting MSW incineration performance.

The identified 12 parameters were divided into three domains:

1. Operational efficiency
2. Environmental impact
3. Economic viability

Some parameters within these domains are primarily sensitive to feedstock quality (for example, the incinerability index, which quantifies the suitability of incinerating MSW), while others are controlled by plant design parameters (for example, pollutant emissions). Instead of evaluating these individually, these characteristics are combined in the formulation to define the integrated incineration performance.

The two economic parameters used in this study are the total cost and total revenue per tonne of waste incinerated. The annuitized capital investment for plant installation and the operational expenditure are both included in the total levelized cost. The rating curves for these characteristics were created using cost and revenue data for the demonstration with Indian MSW plants. By expressing cost and revenue in local currency per tonne and rescaling the breakpoints using either (a) locally representative ranges of levelized cost and revenue per tonne or (b) dimensionless ratios, like the ratio of plant-specific costs to a national median or benchmark facility, the economic rating curves can be applied in other countries while maintaining the same functional form.

2.2 Parameter prioritization and weighting

The next step in the index construction process is quantifying the relative importance of each parameter in affecting the incineration performance. This is done by assigning weights to the identified parameters. The literature reports some studies that assign equal weightages to the constituent parameters (Saaty, 1977). Still, this is generally a poor practice as it assumes that all the parameters affect/ influence the incineration performance to the same extent, which is not the case in real-world scenarios. This oversimplification of assuming equal weights generates noise in the composite index, significantly affecting its robustness and accuracy (Wehbe & Baroud, 2024). Among the other methods that assign weights to parameters (for example, principal component analysis), AHP (Saaty, 1977) is the most widely used and chosen for this study because of its simplicity of calculation for this multi-criteria problem. However, traditional AHP failed to account for the vagueness and uncertainty inherent in experts' knowledge due to the subjective nature of the problem. So, it used to render ambiguous results. This limitation was addressed by incorporating fuzzy set theory (Zadeh, 1965) into the traditional AHP, which constitutes the Fuzzy AHP method. The experts were requested to perform a pairwise comparison among the three criteria (operational efficiency, environmental impact, and economic viability) and the sub-criteria under each criterion. Experts performed the comparisons using linguistic judgements translated to fuzzy pairwise comparison matrices. Table 1 represents the relative scoring scale for FAHP pairwise comparisons and Table 2 represents the pairwise comparison matrix among the three criteria of operational efficiency, economic viability, and environmental impact. Similarly, pairwise

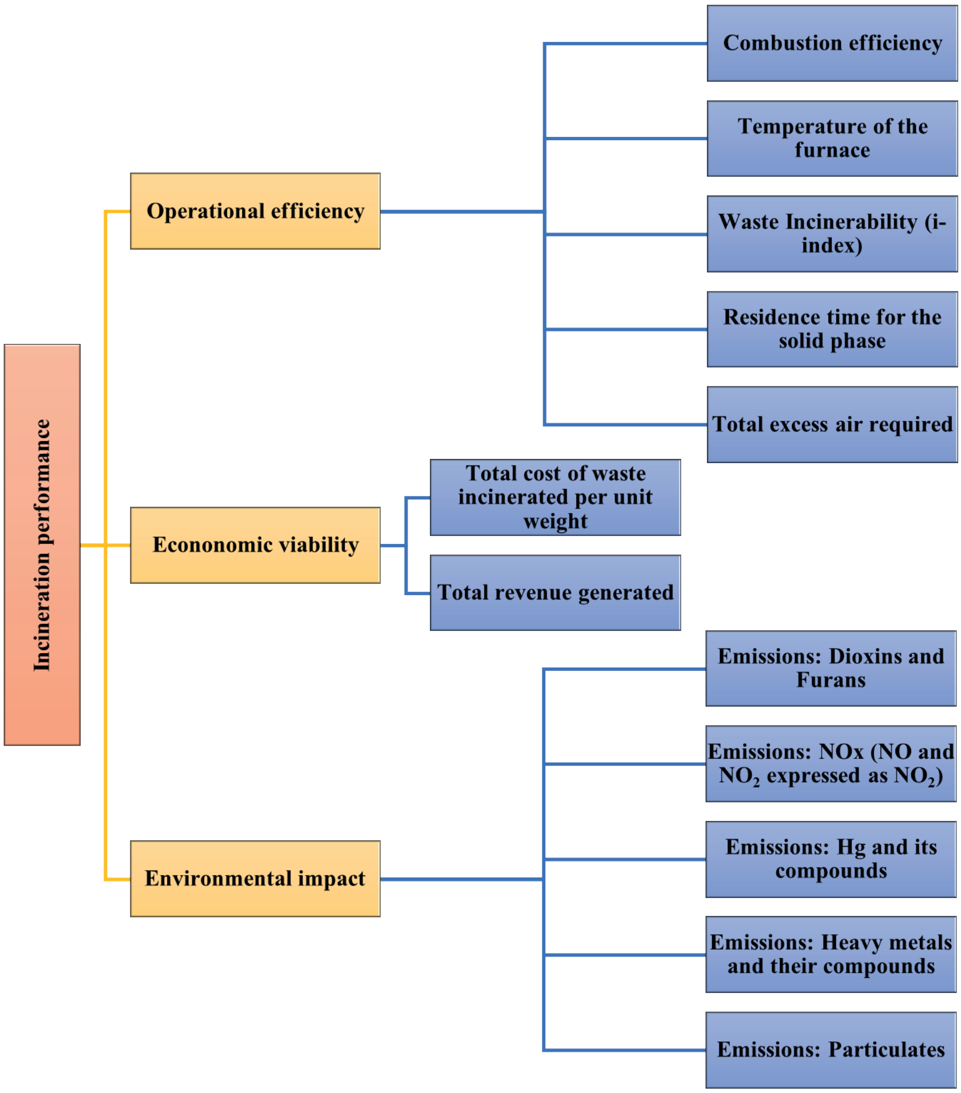

FIGURE 1: Structural hierarchy for parameters affecting MSW incineration performance.

comparisons were conducted among the parameters under each criterion.

Several algorithms evaluate the priority vectors using FAHP, such as extent analysis (Chang, 1996), eigenvalue method (Krejčí, 2017), and the fuzzy inverse of column sum method (Ahmed & Kilic, 2019), to name a few. Statistical metrics were used to make comparisons among the priority weight vectors and calculated using five algorithms to

TABLE 1: Relative scoring scale for FAHP pairwise comparisons.

Linguistic scale	Fuzzy number	Linguistic scale	Reciprocal fuzzy scale
Equally important	1 = (1,1,1)	Equally Unimportant	1 = (1,1,1)
Equal to moderately important	2= (1,2,3)	Equal to Moderately Unimportant	1/2= (1/3,1/2, 1)
Moderately important	3 = (2,3,4)	Moderately Unimportant	1/3 = (1/4, 1/3, 1/2)
Moderately to strongly important	4 = (3,4,5)	Moderately to Strongly Unimportant	1/4 = (1/5, 1/4, 1/3)
Strongly important	5 = (4,5,6)	Strongly Unimportant	1/5 = (1/6, 1/5, 1/4)
Strongly to very strongly important	6 = (5,6,7)	Strongly to Very Strongly Unimportant	1/6 = (1/7, 1/6, 1/5)
Very strongly important	7 = (6,7,8)	Very Strongly Unimportant	1/7 = (1/8, 1/7, 1/6)
Very strongly important to extremely important	8 = (7,8,9)	Very Strongly Important to Extremely Unimportant	1/8 = (1/9, 1/8, 1/7)
Extremely important	9 = (8,9,9)	Extremely Unimportant	1/9 = (1/9, 1/9, 1/8)

TABLE 2: Matrix - Pairwise comparison of the criteria based on the effect on MSW incineration.

Effect on MSW incineration	Operational efficiency	Environmental impact	Economic viability
Operational efficiency	1	a12	a13
Environmental impact	X	1	a23
Economic viability	X	X	1

find the most accurate and robust one (Bisht et al., 2023). From the comparative analysis, logarithmic fuzzy preference programming (LFPP) (Mikhailov, 2003) was the most promising for the current scenario. The LFPP algorithm was used to calculate the normalized priority vectors for the 12 identified parameters. Table 3 shows the weights calculated for the parameters affecting the performance of MSW incineration.

2.3 Normalization of parameters

All the parameters identified and prioritized and known to affect the performance of MSW incineration vary in their units, formulations, and scales. We must bring them to a standard measurement scale to be meaningfully compared and aggregated. This stage is called normalization. Some normalization methods may include categorial scaling, ranking, standardization etc. (Ott, 1978)proposed methods to construct normalization curves by assigning a score to the parameters depending on their numerical values. The indices that were generated using the graphical technique of normalization are: Water quality index (Chidiac et al., 2023), Leachate pollution index (LPI) (Bisht et al., 2022; Kumar & Alappat, 2005) and revised Leachate pollution index(r-LPI) (Bisht et al., 2022), Incinerability index (i-index) (Sebastian et al., 2019), etc. Rating curves were generated, both explicitly and implicitly, for each of the 12 parameters and reflected how the individual parameters contributed to the performance of an MSW incineration facility. The generated curves were then sent to 30 experts for review and consideration. They were encouraged to modify/ redraw the proposed curves as per their understanding. Incorporating

TABLE 3: Priority weights of MSW incineration parameters.

S.No.	Criteria	Parameter	Parameter Weights
1	Operational efficiency	CE	0.247
2		TEMP	0.067
3		i-index	0.091
4		RT(S)	0.053
5		EA	0.054
6	Environmental impact	EM:D&F	0.164
7		EM: NOX	0.075
8		EM: Hg	0.050
9		EM: HM	0.037
10		EM: PART	0.023
11	Economic viability	Total cost	0.078
12		Total revenue	0.061

these modifications to the initially proposed curves gave us the final rating curves. Figure 2 represents the normalization curves for each of the 12 MSW incineration parameters.

2.4 Aggregation

This is the final stage of index construction, which includes selecting a suitable aggregation function to combine all the identified parameters into the final composite index (Den Butter & Van Der Eyden, 1998). This step decides how robust or erroneous the constructed index is. It decides the usability of the index built. Literature suggests several aggregation functions used for constructing various composite indices, namely, weighted and unweighted linear sum, weighted and unweighted root sum power, multiplicative aggregation, maximum and minimum operators, etc. The choice of method depends on the purpose of index construction and its potential users (researchers, academicians, policy makers, etc). If not chosen correctly, an unsuitable aggregation method might lead to manipulated, ambiguous, and eclipsed results. The Environmental Performance Index constructed by Yale University used a Linear weighted addictive function for aggregation, a widely used aggregation function that provides ambiguity-free and non-eclipsed results Click or tap here to enter text. (Block, 2024). After careful consideration of the available literature and the study of sensitivity (which is separately conducted) in the index value by the different aggregation functions, the weighted linear sum method was found to be the most suitable one for aggregating the parameters and quantify them into a single value, representative of the incineration performance. It is calculated as:

$$Incineration\ Performance\ Index,\ IP\text{-}Index = \frac{\sum wipi}{\sum wi}$$

Where wi is the relative weight of the ith parameter, pi is the normalised value of the ith parameter, and ∑wi=1. The aggregated index not only provides a single value indicating the performance of an incineration plant but can also be decomposed into three sub-indices: operational efficiency, environmental impact, and economic viability. These sub-indices enable us to identify which sub-index primarily constrains performance, thereby prioritizing suitable interventions accordingly.

3. RESULTS AND DISCUSSION

This section demonstrates the calculation and application of the Incineration Performance Index by evaluating performance for three hypothetical MSW incineration plants in India. This can help several stakeholders: researchers, plant engineers, multi-level regulatory bodies, and decision makers, to compare and benchmark MSW incineration performance across various plants and suggest measures to optimize the performance.

Table 4 shows the raw and normalized data for the hypothetical plants A, B, and C in India. The raw parameter data is normalized using the normalization curves, generated for each of the 12 parameters. Next, the normalized data is multiplied by the parameter weightages derived by the LFPP-FAHP algorithm. Finally, the IP-index was calculated by aggregating the parameters using a weighted lin-

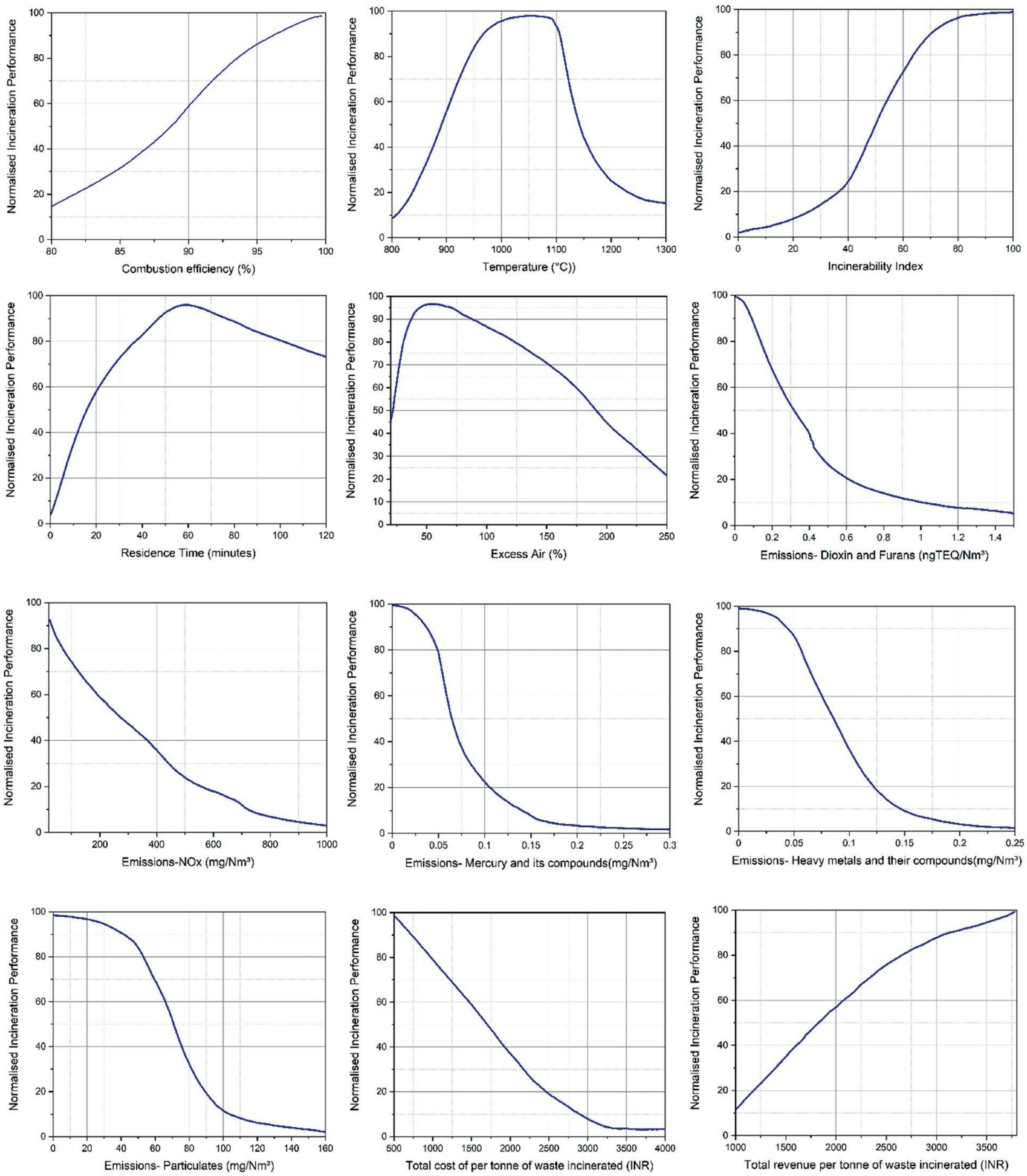

FIGURE 2: Normalization curves for the 12 parameters affecting MSW incineration performance.

ear additive function. Table 5 shows the weighted data for the three plants, for all 12 parameters.

The value of IP-index estimated for the three plants A,B, and C are 87.8, 79.3, and 65.6, respectively. When decomposed into sub-indices, Plant A scores highest in all three domains, which can be attributed to better combustion efficiency, favourable incineration index, more effective emission control system etc. Due to comparatively higher unit costs and lower income per tonne, Plant B's economic sub-index is lower than Plant A's, while having somewhat high operational and environmental sub-indices. The lowest operational and environmental sub-indices are found in Plant C. This demonstration helps the stakeholders to identify and prioritize the specific process, design, or policy actions for performance improvement of an MSW incinerator.

4. CONCLUSIONS

The incineration performance index developed in this study to quantify the overall performance of MSW incineration systems by holistically integrating the operation-

TABLE 4: Raw and normalized data for Plant A, B, C.

S.No	Parameter	Weight	Planta raw data	Planta normalized data	Plantb raw data	Plantb normalized data	Plantc raw data	Plantc normalized data
1	CE	0.247	99.4	98.25	96.4	90.83	94.4	83.92
2	TEMP	0.067	1060	97.95	900	56.09	850	26.44
3	i-index	0.091	76	94.38	64	80.6	59	70.78
4	RT(S)	0.053	55	95.23	45	88.08	40	82.84
5	EA	0.054	60	96.42	80	92	100	86.68
6	EM: D&F	0.164	0.03	98.09	0.04	97.56	0.12	83.72
7	EM: NOX	0.075	170	63.04	200	58.81	420	33.02
8	EM: Hg	0.050	0.01	98.84	0.03	93.42	0.06	57.71
9	EM: HM	0.037	0.02	97.77	0.041	91.80	0.07	65.42
10	EM: PART	0.023	20	96.52	35	92.77	69	54.18
11	Total cost	0.078	3100	6.18	3800	3.27	3900	3.36
12	Total revenue	0.061	3780	98.68	3000	86.40	2500	74.52

TABLE 5: Weighted data for Plant A, B, and C.

S.No	Parameter	PlantA weighted data	PlantB weighted data	PlantC weighted data
1	CE	24.268	22.435	20.728
2	TEMP	6.563	3.758	1.771
3	i-index	8.589	7.335	6.441
4	RT(S)	5.047	4.668	4.391
5	EA	5.207	4.968	4.681
6	EM: D&F	16.087	16.000	13.730
7	EM: NOX	4.728	4.411	2.477
8	EM: Hg	4.942	4.671	2.886
9	EM: HM	3.617	3.397	2.421
10	EM: PART	2.220	2.134	1.246
11	Total cost	0.482	0.255	0.262
12	Total revenue	6.019	5.270	4.546
	IP-index (~)	**87.8**	**79.3**	**65.6**

al, environmental, and economic parameters in the form of a single composite score. It shows the integration of expert opinion and quantitative analysis in addressing a multi-criteria environmental challenge: MSW incineration. This study was a step-by-step demonstration of the construction of a rigorous and handy tool that could be used to evaluate MSW incineration performance quantitatively and with ease. Its application is demonstrated for three hypothetical MSW incineration plants with overall scores of around 87.8, 79.3, and 65.6. This effectively helps the stakeholders to identify and differentiate the gaps in technology levels, reveal the dimensions where the plants underperform, making room for improvements. It replaces the traditional approaches (for example techno-economic analysis, loss on ignition, LCA based evaluations etc.) of performance evaluation by providing a handy, holistic, transparent and easy to communicate metric which can be estimated using routinely available plant data. This tool can compare the MSW incineration performance of plants nationally and internationally. It can help set benchmarks best practices, making the MSW incineration process more efficient, sustainable, and compliant with regulatory standards.

5. FUTURE PERSPECTIVES

The present work demonstrates the construction and demonstration of the Incineration Performance Index using the hypothetical data for three MSW incineration plants. Future research should validate and apply it to relevant time-series data from different operating MSW plants across varying regulatory environments. Detailed uncertainty and sensitivity analysis of the entire methodology- from assigning weightages to the parameters, development of sub-index curves, and aggregation of the parameters- would further increase the robustness and credibility of the index.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Indian Institute of Technology for providing the research facilities, stimulating and academic environment for carrying out the research.

REFERENCES

Ahmed, F., & Kilic, K. (2019). Fuzzy Analytic Hierarchy Process: A performance analysis of various algorithms. Fuzzy Sets and Systems, 362, 110–128. https://doi.org/10.1016/j.fss.2018.08.009

Bisht, T. S., Kumar, D., & Alappat, B. J. (2022). Revised leachate pollution index (r-LPI): A tool to quantify the contamination potential of landfill leachate. Process Safety and Environmental Protection, 168, 1142–1154. https://doi.org/10.1016/j.psep.2022.10.052

Bisht, T. S., Kumar, D., & Alappat, B. J. (2023). Deriving and comparing priority vectors for revised-leachate pollution index (r-LPI) using three fuzzy analytic hierarchy process. Environmental Progress and Sustainable Energy, 42(1). https://doi.org/10.1002/ep.13931

Block, S. , E. J. W. , E. D. C. , de S. A. , W. Z. A. (2024). Environmental Performance Index. . New Haven. CT: Yale Center for Environmental Law & Policy. Epi.Yale.Edu.

Chang, D.-Y. (1996). EUROPEAN JOURNAL OF OPERATIONAL RESEARCH Applications of the extent analysis method on fuzzy AHP. In European Journal of Operational Research (Vol. 95).

Chidiac, S., El Najjar, P., Ouaini, N., El Rayess, Y., & El Azzi, D. (2023). A comprehensive review of water quality indices (WQIs): history, models, attempts and perspectives. In Reviews in Environmental Science and Biotechnology (Vol. 22, Number 2, pp. 349–395). Springer Science and Business Media B.V. https://doi.org/10.1007/s11157-023-09650-7

Den Butter, F. A. G., & Van Der Eyden, J. A. C. (1998). A pilot index for environmental policy in The Netherlands. In Energy Policy (Vol. 26, Number 2).

Güdemann, L., & Münnich, R. (2023). Quality and Sensitivity of Composite Indicators for Sustainable Development. Austrian Journal of Statistics, 52(5), 82–100. https://doi.org/10.17713/ajs.v52i5.1539

Ishikawa, A., Amagasa, M., Tomizawa, G., Tatsuta, R., & Mieno, H. (1993). The Max-Min Delphi Method and Fuzzy Delphi Method Via Fuzzy Integration. Fuzzy Sets and Systems , 55, 241–253.

Krejčí, J. (2017). Fuzzy eigenvector method for obtaining normalized fuzzy weights from fuzzy pairwise comparison matrices. Fuzzy Sets and Systems, 315, 26–43. https://doi.org/10.1016/j.fss.2016.03.006

Kumar, D., & Alappat, B. J. (2005). Analysis of leachate pollution index and formulation of sub-leachate pollution indices. Waste Management & Research: The Journal for a Sustainable Circular Economy, 23(3), 230–239. https://doi.org/10.1177/0734242X05054875

Mikhailov, L. (2003). Deriving priorities from fuzzy pairwise comparison judgements. In Fuzzy Sets and Systems (Vol. 134). www.elsevier.com/locate/fss

Ott, W. R. (1978). Environmental Indices: Theory and Practice (Ann Arbor, Ed.). Ann Arbor Science Publishers Inc.

Ouda, O. K. M., Cekirge, H. M., & Raza, S. A. R. (2013). An assessment of the potential contribution from waste-to-energy facilities to electricity demand in Saudi Arabia. Energy Conversion and Management, 75, 402–406. https://doi.org/10.1016/j.enconman.2013.06.056

Report of the Task Force on Waste to Energy (Volume I) (In the context of Integrated MSW Management) Planning Commission Submission Certificate of the Report of the Task Force. i Preface ii Acknowledgements v. (2014).

Saaty, T. L. (1977). A Scaling Method for Priorities in Hierarchical Structures. In Journal 01: Mathematical Psychology (Vol. 15).

Sebastian, R. M., Kumar, D., & Alappat, B. J. (2019). A technique to quantify incinerability of municipal solid waste. Resources, Conservation and Recycling, 140, 286–296. https://doi.org/10.1016/j.resconrec.2018.09.022

Wang, Q., Gong, D., Huang, Z., Peng, C., Chen, J., Luo, J., Zhu, J., & Luo, Q. (2024). Simulation Study on the Stabilization Control Performance of Low-Calorific-Value Waste Combustion in Waste Incinerators. ACS Omega, 9(49), 48586–48597. https://doi.org/10.1021/acsomega.4c07552

Wehbe, C., & Baroud, H. (2024). Limitations and considerations of using composite indicators to measure vulnerability to natural hazards. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-68060-z

Zadeh, L. A. (1965). Fuzzy S e t s *. In INFOR~ATIO~ AND CONTROL (Vol. 8).